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EFFECT OF THROTTLING ON INTERFACE BEHAVIOR AND LIQUID RESIDUALS IN WEIGHTLESSNESS

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16. Abstract

An experimental investigation was conducted to study liquid-vapor interface behavior and subsequent vapor ingestion in a flat-bottomed cylindrical tank following a single-step throttling in outflow rate in a weightless environment. A throttling process in which the final Weber number was one-tenth of the initial Weber number tended to excite large-amplitude symmetric slosh, with the amplitude generally increasing as initial Weber number increased. As expected, liquid residuals were lower than those obtained without throttling and, for moderate values of initial Weber number, could be adequately predicted by assuming that all draining took place at the final Weber number. At larger values of Weber number, residuals tended to be lower than this predicted value.

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EFFECT OF THROTTLING ON INTERFACE BEHAVIOR AND LIQUID RESIDUALS IN WEIGHTLESSNESS

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SUMMARY

An experimental investigation was conducted to study the behavior of the liquid-vapor interface, as well as the vapor ingestion phenomenon, in a flat-bottomed cylindrical tank in weightlessness following a single-step throttling of the outflow rate. A step change of 10:1 in outflow Weber number was found to excite large-amplitude symmetric slosh whose amplitude generally increased with increasing initial Weber number. Liquid residuals at vapor ingestion were lower than those obtained without throttling and, for moderate values of initial Weber number, could be predicted adequately by assuming that all draining occurred at the final, or throttled, Weber number. At larger values of Weber number, liquid residuals tended to be lower than those predicted by using this method.

INTRODUCTION

The phenomenon of outflow from an unbaffled tank in a weightless environment has received considerable attention in the literature. The initial study in this area was a photographic study of the outflow process from a cylindrical container (ref. 1). Additional studies examined the distortion of the liquid-vapor interface which occurs during outflow (ref. 2) and determined critical and vapor ingestion heights in both flat- and hemispherical-bottomed cylinders in zero gravity and in normal gravity (refs. 3 and 4). All these studies have shown that a considerable quantity of liquid remains in the tank as residual at the time that vapor is ingested into the outlet line.

Various methods including dielectrophoresis, acceleration, surface tension, contouring of the outlet line, and positive displacement devices have been suggested as a possible means of reducing the magnitude of the residual remaining in the tank at vapor ingestion. Another technique is the use of outflow modulation, or throttling. The ideal

manner in which to utilize this technique would be to initiate outflow at the maximum outflow rate which would not cause vapor to be ingested for the available height of liquid in the tank. The outflow rate would then be continually reduced as the tank liquid level decreased, in all cases draining at the maximum outflow rate which could be tolerated for a given height of liquid in the tank. Obviously, such a control system would be extremely difficult, if not impossible, to implement. A simpler method, although not optimum from the standpoint of minimizing draining time, might be to use a single or perhaps a series of step changes in outflow rate during the draining process.

This report examines the behavior of the liquid-vapor interface and the vapor ingestion following a single-step change, or throttling, of the outflow rate. Results are presented in photographic and graphic form which describes the behavior of the liquid-vapor interface and the liquid residuals obtained when the Weber number is throttled to one-tenth of its initial value.

APPARATUS

The Lewis Research Center's Zero-Gravity Research Facility was used to obtain the experiment data for this investigation. A complete description of the facility, the experiment vehicle, and the test procedure can be found in the appendix.

Experiment Tanks

A schematic drawing of a typical experiment tank is shown in figure 1. The tanks were flat-bottomed right-circular cylinders 2 and 4 centimeters in radius and machined from cast acrylic plastic which was polished to optical clarity. Ends for the tanks were machined from stainless-steel plates and were equipped with O-rings to provide a seal with the cylindrical center sections. Each tank was fitted with a cylindrical pressurant-gas inlet and a liquid outlet line, both located along the tank centerline. The 2-centimeter-radius tank had an outlet line radius equal to one-tenth of the tank radius, while the 4-centimeter-radius tank had outlets of either one-tenth or one-twentieth of the tank radius. At the pressurant-gas inlet, each tank was fitted with an air deflector plate the diameter of which was equal to the tank radius. This baffle was positioned 1/2 tank radius from the top of the tank and prevented the direct impingement of the pressurant gas on the liquid surface during draining. Outlet lines for the tanks had a run of at least 15 outlet line diameters prior to entering the throttle valve. The throttle valve was

a solenoid-driven thin plate which could be adjusted to provide the proper opening to give the desired ratio of final to initial flow rate.

Test Liquids

The liquids used in this investigation and their pertinent physical properties are presented in table I. All liquids used had a 0^{o} static contact angle on the test containers to duplicate the contact angle of most propellants on typical tankage material. In order to improve the photographic quality of data films, a small quantity of dye was added to each of the liquids. The addition of the dye had no measurable effects on the fluid properties.

RESULTS AND DISCUSSION

Effect of Throttling on Interface Behavior

A single-step throttling process in which the Weber number was reduced to one-tenth of its initial value tended to excite large-amplitude symmetric slosh which manifested itself in three distinct regimes of liquid-vapor interface behavior. Photographic sequences illustrating each regime are presented in figure 2. In each sequence, the first photograph indicates the configuration in normal gravity; the second, the configuration just prior to the initiation of throttling; the third, the configuration shortly after throttling; and finally, the configuration at the instant of vapor ingestion into the tank outlet. Initial fillings (measured in height above the tank outlet in normal gravity) were 3 tank radii.

The first sequence (fig. 2(a)) shows the no-geyser regime. In this test, the initial Weber number was 0.3, the test liquid was anhydrous ethanol, and the tank was 2 centimeters in radius with a 0.2-centimeter-radius outlet. (Weber number is a dimensionless parameter, the ratio of the square of the outflow rate to the product of specific surface tension and the cube of the tank radius.) Just after throttling the interface has been flattened, but no axial geyser of liquid has formed.

Figure 2(b) shows the stable geyser regime. In this test the initial Weber number was 10.9, the test liquid was anhydrous ethanol, and the tank was 4 centimeters in radius and had a 0.4-centimeter-radius outlet line. At about 0.4 second after throttling the interface has been flattened, and an axial geyser which was formed has reached its peak height. Shortly thereafter the geyser receded into the bulk liquid. In this test, the geyser reached a maximum height of about 2.7 centimeters.

An unstable geyser is depicted in figure 2(c). For this test, the initial Weber number was 11.7, the tank was 4 centimeters in radius with a 0.4-centimeter-radius outlet, and the test liquid was trichlorotrifluoroethane. The liquid-vapor interface shape at the time of throttling is very similar to that shown in figure 2(b). However, after throttling occurs, a large axial geyser forms and grows in height, eventually "pinching off" to form a single drop of liquid which moves to the opposite end of the tank.

The liquid-vapor interface behavior immediately following a single-step change in Weber number ($We_{final} = 1/10\ We_{initial}$) is very similar to that which occurs following termination of outflow (ref. 5) with regard to the delineation of the geyser - no-geyser regime. A plot of the data in the format used in reference 5 is presented in figure 3. Although no attempt was made to vary the initial fill in the present tests (and hence, only a slight variation in relative interface displacement occurred), the agreement of the present data with that of reference 5 is reasonably close over a fairly wide range of initial Weber numbers. Because of the agreement at a throttling ratio of 10:1, it should be expected that greater throttling ratios (i.e., 100:1 or 1000:1) would agree at least as well.

Effect of Throttling on Liquid Residuals

The magnitude of the liquid residuals which occur in flat-bottomed cylinders during outflow in weightlessness as a function of initial fill and outflow Weber number has been documented in the literature (ref. 3). It is to be expected from reference 3 data, that as Weber number is decreased (below about 2.5), the amount of liquid residual would also decrease accordingly. Thus, it is possible to generate, from previous data, two curves which might be expected to bracket the data obtained in this study. These curves, as well as the experiment data, are presented in figure 4. The uppermost curve shows the residual expressed as a percentage of initial liquid volume which would occur if the outflow were continued at the initial Weber number. The lower curve denotes the residual which would be expected if all draining took place at the final Weber number. Assuming that the liquid-vapor interface was not flattened or displaced upward by the throttling, the residuals obtained should fall between the two bounding curves. However, the symmetric slosh excited by the throttling caused the interface to flatten and, in some cases, to form a geyser. Thus, draining took place from an effectively larger liquid height above the outlet. As a result, draining times at the final Weber number were considerably greater than anticipated, primarily because of the time required for the interface disturbance to damp out.

As discussed in the previous section, as the outflow Weber number increased so did the magnitude of the upward displacement of the interface. At a constant throttling ratio,

this relation is reflected in lower values of liquid residuals as the initial Weber number increases. For initial Weber numbers between about 0.25 and 4, liquid residuals were about 30 percent of the initial liquid volume. In contrast, residuals of about 35 to 60 percent would be expected without throttling. Above initial Weber numbers of 5, residuals ranged from about 20 to 8 percent of the initial liquid volume, compared with approximately 60 percent without throttling.

As shown in figure 4, for moderate values of initial Weber number ($0.5 < We < 4$), the quantity of liquid residual remaining in the tank at vapor ingestion was adequately predicted by assuming that the entire draining had taken place at the final Weber number. However, at large values of initial Weber number ($We > 5$), the obtained residuals were much lower than this predicted value.

CONCLUDING REMARKS

This experimental investigation was conducted to assess the effect of a single-step change in the outflow rate on liquid-vapor interface behavior, subsequent ingestion of vapor into the outlet line, and associated liquid residuals. Tanks employed in the study were flat-bottomed right-circular cylinders having inside radii of 2 and 4 centimeters. Each tank was fitted with an outlet line that was circular in cross section and located along the tank centerline at the tank bottom. Outlet line radii were 0.2 centimeter in the 2-centimeter-radius tank and 0.2 and 0.4 centimeter in the 4-centimeter-radius tank. Test liquids were anhydrous ethanol and trichlorotrifluoroethane. Initial fillings measured in normal gravity were 3 tank radii. In all tests, the ratio of the final Weber number to the initial Weber number was 1:10.

It was observed that the throttling process influenced the behavior of the liquid-vapor interface by exciting large-amplitude symmetric slosh. Depending on the initial Weber number, the sloshing was reflected in a liquid-vapor interface which was either flattened, formed in a stable geyser which eventually receded into the bulk liquid, or formed in an unstable geyser which broke into one or more droplets which moved to the tank end opposite the outlet line. The magnitudes of the Weber numbers separating the geyser - no-geyser regime were found to be essentially the same as those observed to separate the same two regimes in an earlier study in which outflow was terminated at some point during the draining process.

As expected, throttling tended to decrease liquid residuals below those which would have occurred had the initial Weber number been maintained until vapor ingestion. For moderate values of the initial Weber number ($0.5 < We < 4$), the quantity of liquid residual was adequately predicted by assuming that the entire draining had occurred at the final Weber number with no interface distortion. However, at larger values of initial

Weber number (We $>$ 5), the residuals obtained were lower than this predicted value. The decrease was primarily attributed to a combination of the increased interface distortion after throttling at the higher Weber numbers and the length of time required to damp out the interface disturbance.

The attractiveness of step throttling of the outflow rate would seem to be limited to those applications in which the initial Weber number is sufficiently high to create significant interface distortion during the initial draining phase. At low values of initial Weber number, throttling would only slightly reduce residuals since the amplitude of the slosh excited would be small, and the only reduction in residuals would result from the difference in critical heights between the initial and final Weber numbers.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 25, 1974,
502-24.

APPENDIX - APPARATUS AND PROCEDURE

Facility

The experiment data for this study were obtained in the Zero-Gravity Research Facility at the Lewis Research Center. A schematic diagram of this facility is shown in figure 5. The facility consists of a concrete-lined 8.5-meter-diameter shaft that extends 155 meters below ground level. A steel vacuum chamber, 6.1 meters in diameter and 143 meters high, is contained within the concrete shaft. The pressure in this vacuum chamber is reduced to 13.3 N/m^2 by using the Center's wind tunnel exhaust system located within the facility.

The ground-level service building has as its major elements a shop area, a control room, and a clean room. Assembly, servicing, and balancing of the experiment vehicle are accomplished in the shop area. Tests are conducted from the control room, shown in figure 6, which contains the exhauster control system, the experiment vehicle predrop checkout and control system, and the data retrieval system. Those components of the experiment which come in contact with the test fluid are prepared in the facility's class 10 000 clean room, shown in figure 7. The major elements contained within this room are an ultrasonic cleaning system (fig. 7(a)) and a class 100 laminar-flow station (fig. 7(b)) for preparing those experiments requiring more than normal cleanliness.

Mode of operation. - The Zero-Gravity Research Facility has two modes of operation. One is to allow the experiment vehicle to fall freely from the top of the vacuum chamber, which results in nominally 5 seconds of free-fall time. The second mode is to project the experiment vehicle upward from the bottom of the chamber by a high-pressure pneumatic accelerator located on the vertical axis of the chamber. The total up-and-down trajectory of the experiment vehicle results in nominally 10 seconds of free-fall time. The 5-second mode of operation was employed in this study.

In either mode of operation, the experiment vehicle falls freely; that is, no guide wires, electrical lines, and so forth are connected to the vehicle. Therefore, the only force (aside from gravity) acting on the freely falling experiment vehicle is residual air drag. This results in an equivalent gravitational acceleration acting on the experiment which is estimated to be of the order of 10^{-5} g's maximum.

Recovery system. - After the experiment vehicle has traversed the total length of the vacuum chamber, it is decelerated in a 3.6-meter-diameter, 6.1-meter-deep container which is located on the vertical axis of the chamber and filled with small pellets of expanded polystyrene. The deceleration rate, averaging about 35 g's, is controlled by the flow of these pellets in the annular area between the experiment vehicle and the wall of the deceleration container. The container is mounted on a cart which can be retracted prior to using the 10-second mode of operation. In this mode of operation, the

cart is deployed after the experiment vehicle is projected upward by the pneumatic accelerator. The deceleration container mounted on the cart is shown in figure 8.

Experiment Vehicle

The experiment vehicle used to obtain the data for this study is shown in figure 9. The vehicle consists of a telemetry system (contained in the top fairing) and an experiment section (housed in the cylindrical midsection).

Telemetry section. - The onboard telemetry system which is used to collect data is a standard Inter-Range Instrumentation Group(IRIG) FM/FM 2200-megahertz telemeter. It is used during a test drop to record as many as 18 channels of continuous data. The system frequency range extends to 2100 hertz. The telemetered data are recorded on two high-response recording oscillographs located in the control room.

Experiment section. - The experiment section, shown in figure 10, consists of the test tank, a pressure bottle, a collection tank, a photographic and lighting system, a digital clock, and an electrical system to operate the various components. The test tank is indirectly illuminated by means of a backlighting system contained in the experiment housing which provides sufficient light so that the behavior of the liquid-vapor interface can be recorded by a high-speed 16-millimeter camera. A clock with a calibrated accuracy of ± 0.01 second is positioned within the field of view of the camera to provide an indication of the elapsed time during the weightless drop. The electrical components (including the solenoid-operated throttle valve) onboard the package are operated through a control box and receive their power from rechargeable nickel cadmium cells.

Test Procedure

The test containers were cleaned ultrasonically prior to each test in the facility's clean room (fig. 7). The cleaning consisted of ultrasonic immersion in a solution of detergent and water, rinsing with a solution of distilled water and methanol, and drying in a warm-air dryer.

The containers were then mounted on the experiment package, and liquid was added to fill the test tank to the desired fill level. Pressure was added to the accumulator bottles, and the throttle valve was adjusted to give the proper throttling ratio.

During a drop, a predetermined time increment was allowed so that the liquid-vapor interface could reach its low point in the first pass through its equilibrium configuration. At this time, outflow was initiated and continued until vapor ingestion into the tank outlet was imminent, at which time the throttle valve was actuated to reduce the outflow

rate. Electrical timers carried onboard the experimental vehicle were set to control the initiation and duration of the above-mentioned functions on each drop.

After all predrop functions were set, the experiment vehicle was positioned at the top of the vacuum chamber as shown in figure 11. It was suspended by the support shaft on a hinged-plate release mechanism. During vacuum chamber pumpdown and prior to release, monitoring of the experiment vehicle system was accomplished through an umbilical cable attached to the top of the support shaft. Electrical power was supplied by ground equipment. The system was switched to internal power a few minutes before release. The umbilical cable was remotely pulled from the shaft 0.5 second prior to release. The experiment vehicle was released by hydraulically shearing a bolt that was holding the hinged plate in the closed position. No measurable disturbances were imparted to the experiment by this release procedure.

The total free-fall test time obtained in this mode of operation was 5.16 seconds. During the test drop, the vehicle's trajectory and deceleration were monitored on closed-circuit television. Following the test drop, the vacuum chamber was vented to the atmosphere and the experiment vehicle was returned to ground level.

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4. Berenyi, Steven G.; and Abdalla, Kaleel L.: Vapor Ingestion Phenomena in Hemispherically Bottomed Tanks in Normal Gravity and in Weightlessness. NASA TN D-5704, 1970.

5. Grubb, Lynn S.; and Petrash, Donald A.: Experimental Investigation of Interfacial Behavior Following Termination of Outflow in Weightlessness. NASA TN D-3897, 1967.

TABLE I. - PROPERTIES OF TEST LIQUIDS

[Static contact angle with cast acrylic plastic in air, 0^{o}.]

Liquid	Surface tension at 20^{o} C, σ, N/cm (10^{5} dynes/cm)	Density at 20^{o} C, ρ, g/cm^{3}	Viscosity at 20^{o} C, μ, g/(cm)(sec)	Specific surface tension, β, cm^{3}/sec^{2}
Anhydrous ethanol	22.3×10^{-5}	0.79	1.2×10^{-2}	28.3
Trichloro-trifluoro-ethane	$18\ 6\times10^{-5}$	1.58	$.7\times10^{-2}$	11.8

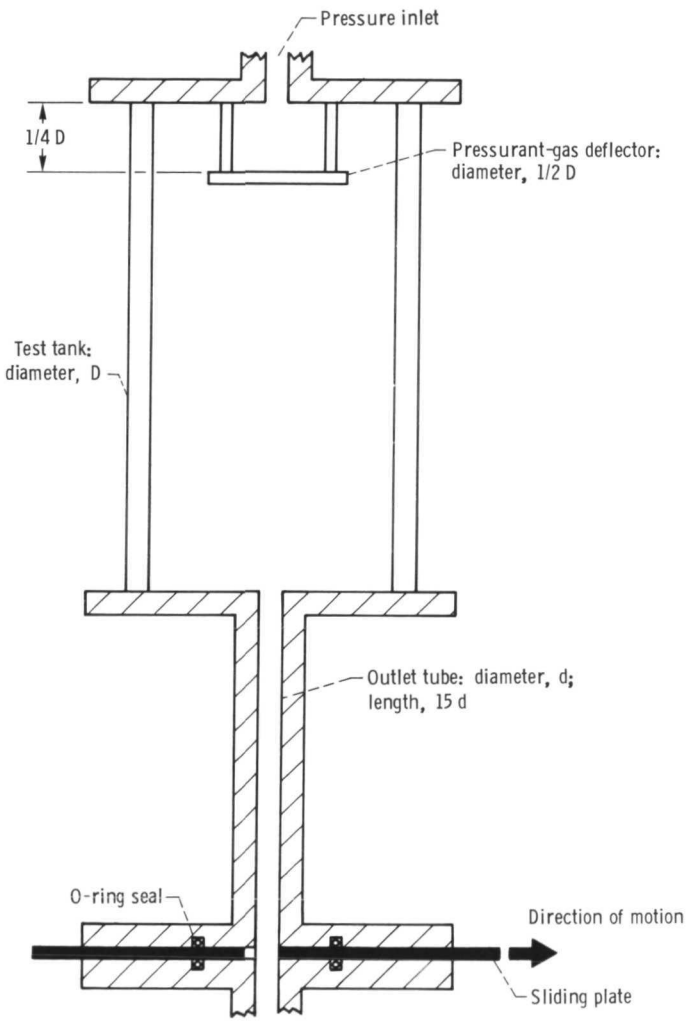
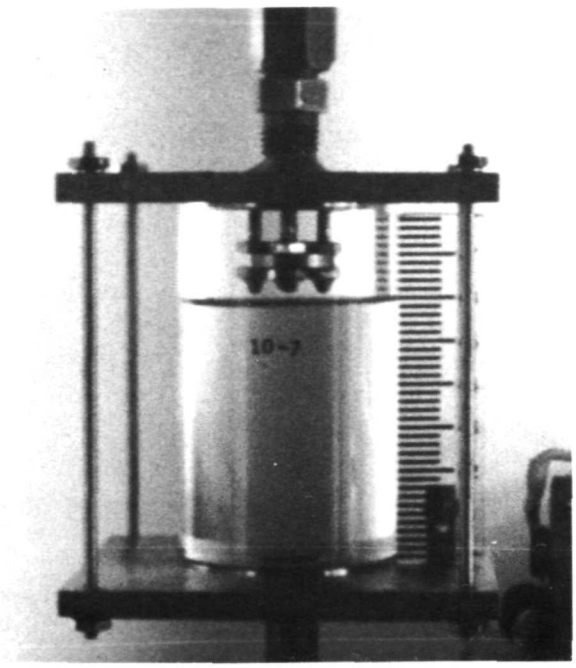
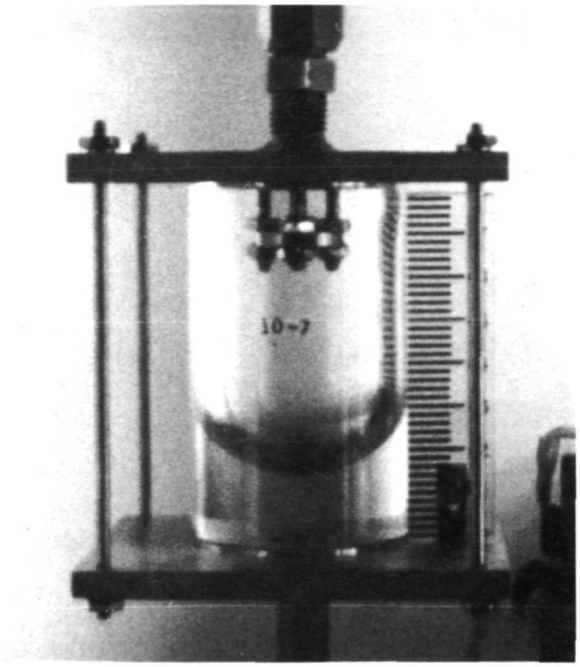


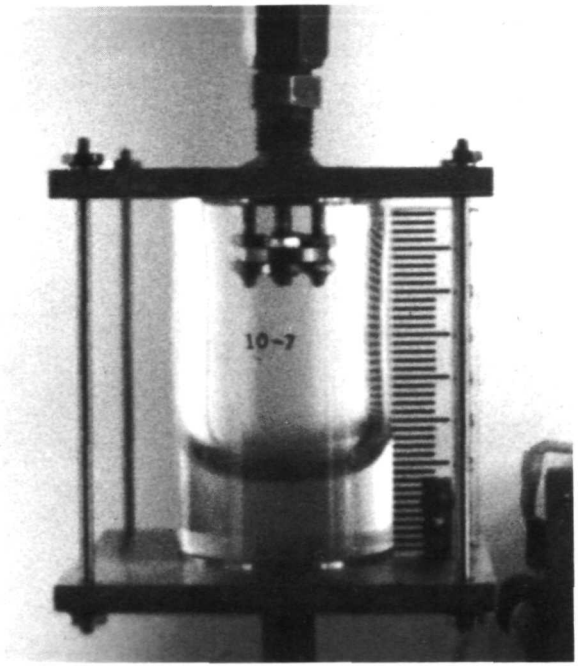
Figure 1. - Schematic drawing of typical test tank.



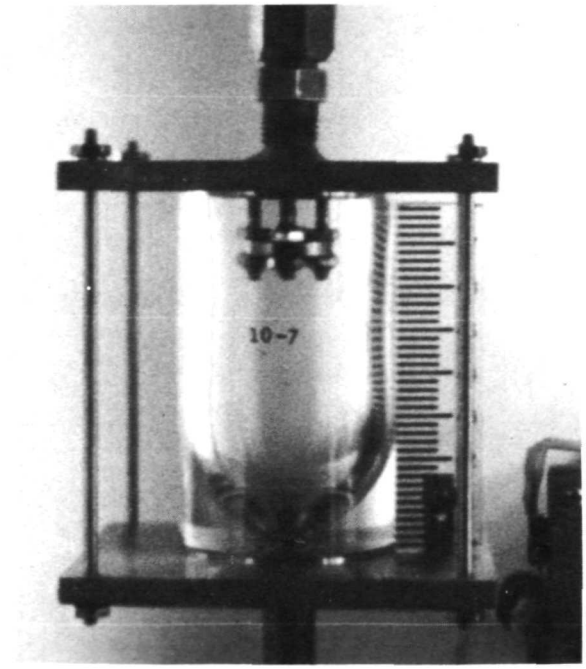
Normal gravity; time, 0 second



Start of throttling; time, 1.25 seconds



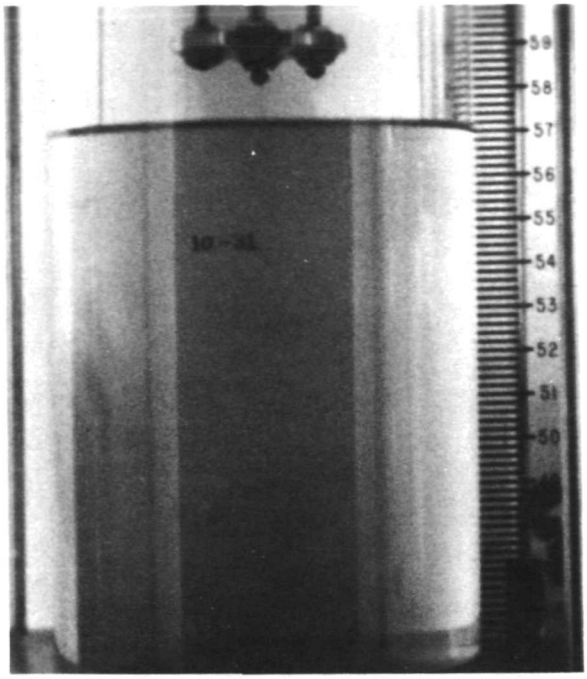
After throttling; time, 1.39 seconds



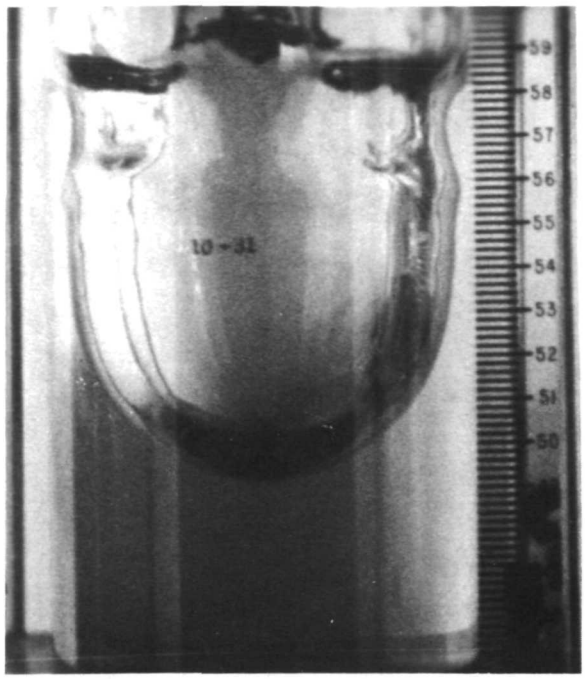
At vapor ingestion; time, 2.06 seconds

(a) No geyser. Tank radius, 2 centimeters; outlet line radius, 0.2 centimeter; liquid, ethanol; initial Weber number, 0.3.

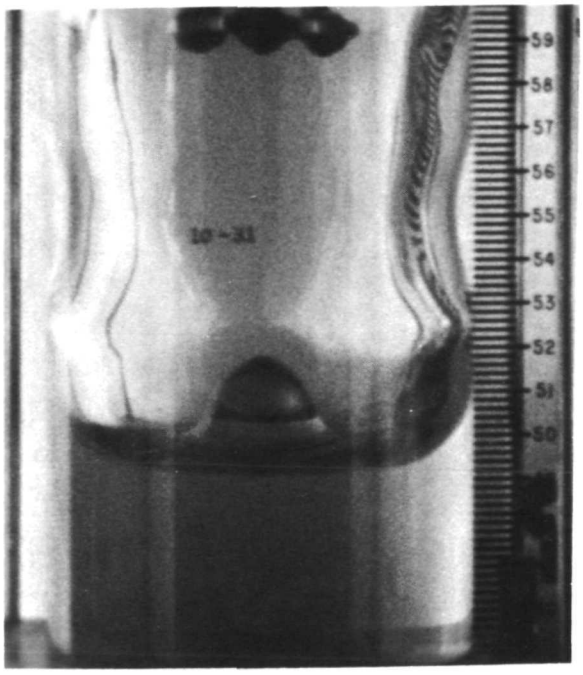
Figure 2. - Liquid-vapor interface behavior during throttled draining. Ratio of final Weber number to initial Weber number, 1:10.



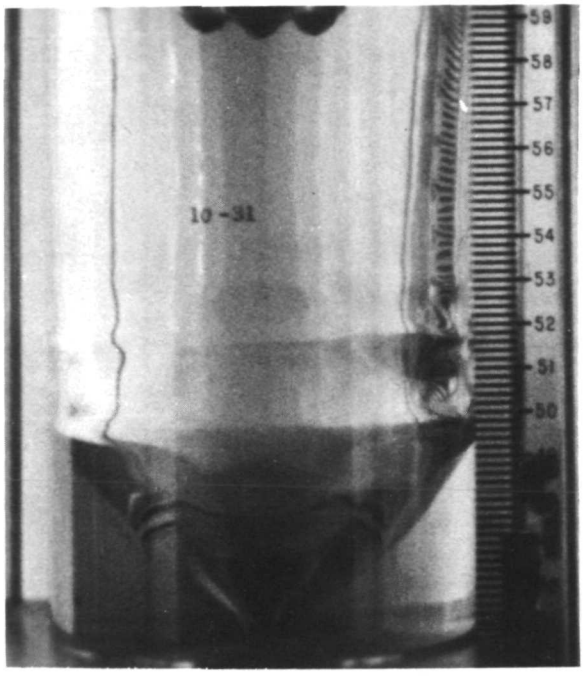
Normal gravity; time, 0 second



Start of throttling; time, 1.15 seconds



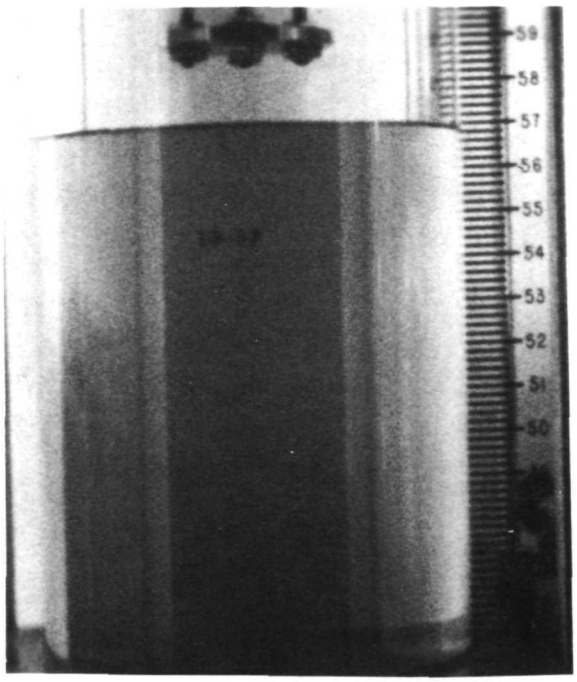
After throttling; time, 1.55 seconds



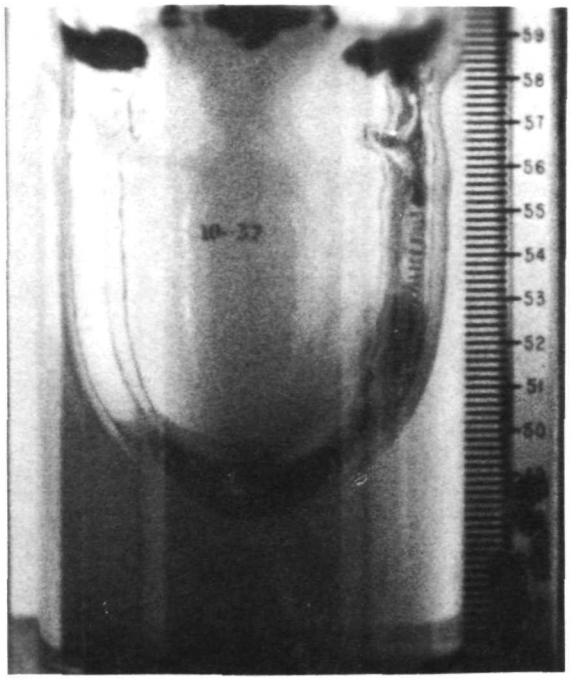
At vapor ingestion; time, 2.32 seconds

(b) Stable geyser. Tank radius, 4 centimeters; outlet line radius, 0.4 centimeter; liquid, ethanol; initial Weber number, 10.9.

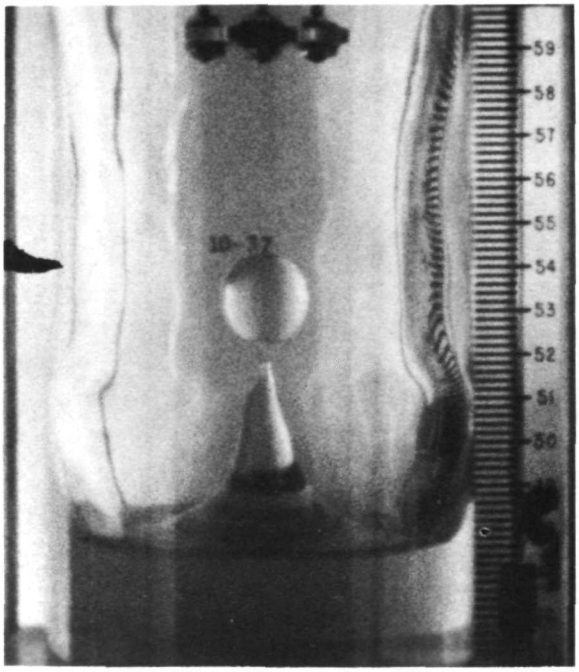
Figure 2. - Continued



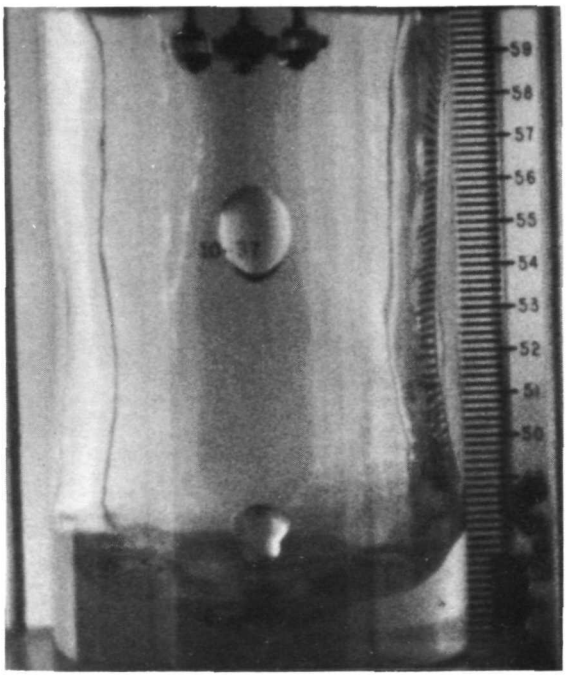
Normal gravity; time, 0 second



Start of throttling; time, 1.81 seconds



After throttling; time, 2.82 seconds



At vapor ingestion; time, 3.32 seconds

(c) Unstable geyser. Tank radius, 4 centimeters; outlet line radius, 0.4 centimeter; liquid, trichlorotrifluoroethane; initial Weber number, 11.7.

Figure 2. - Concluded.

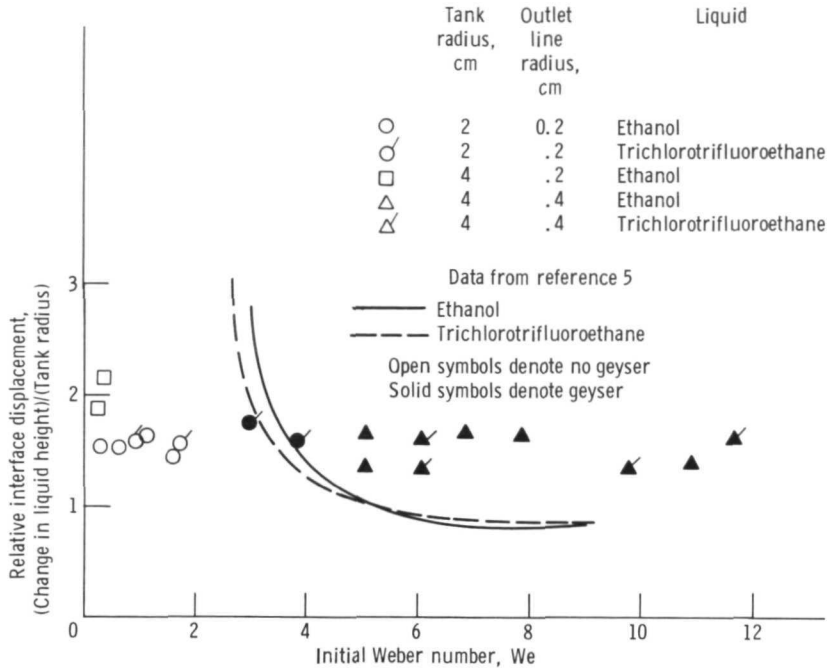


Figure 3. - Interface behavior following single-step throttling. Ratio of final Weber number to initial Weber number, 1:10.

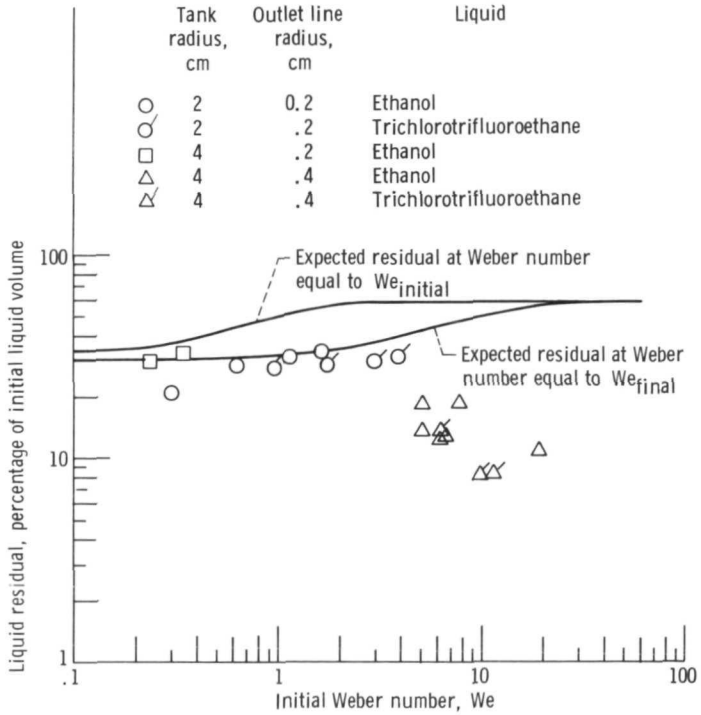


Figure 4. - Percentage of liquid residual as function of initial Weber number. Ratio of final Weber number to initial Weber number, 1:10.

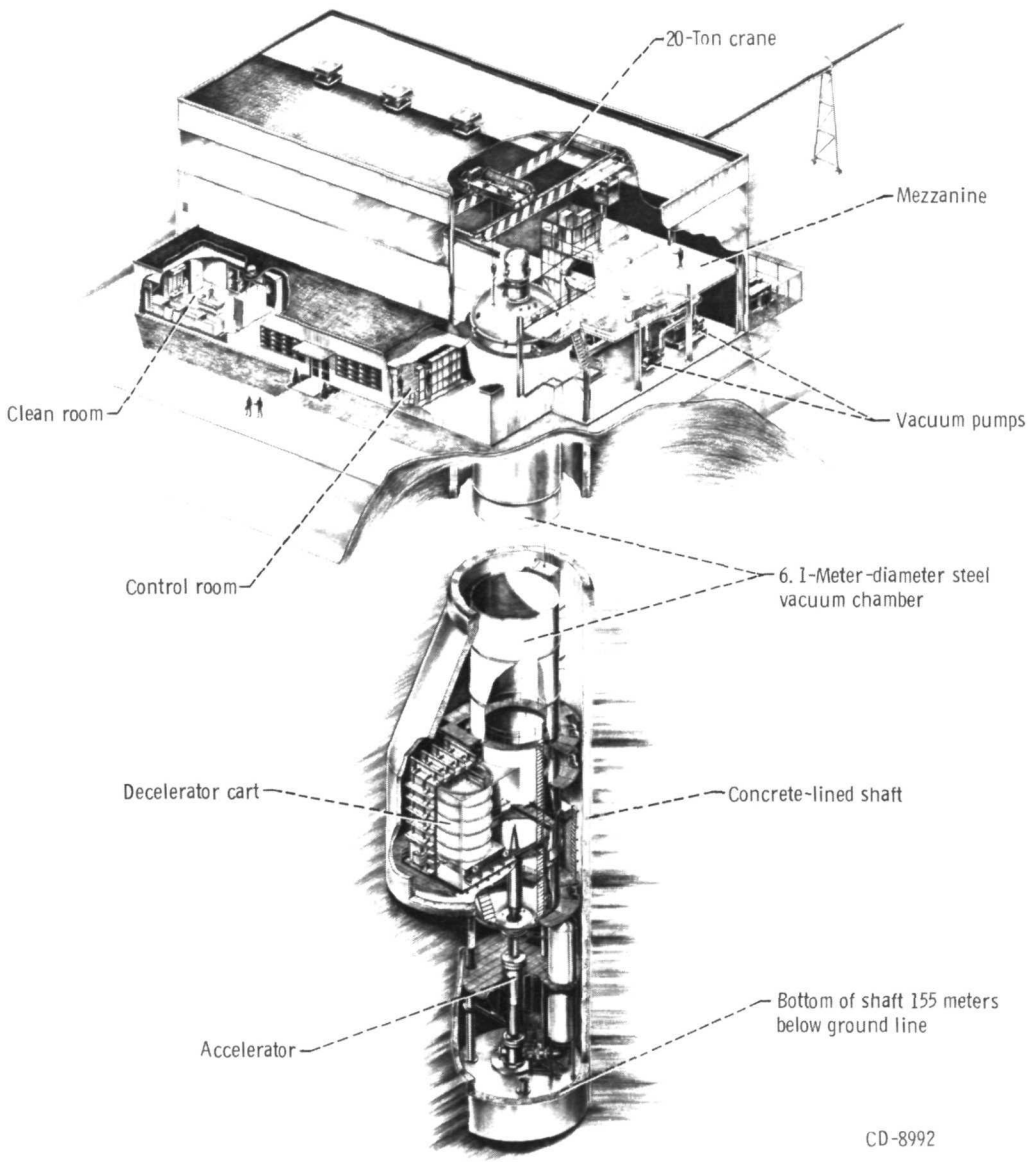


Figure 5. - Schematic diagram of Zero-Gravity Research Facility.

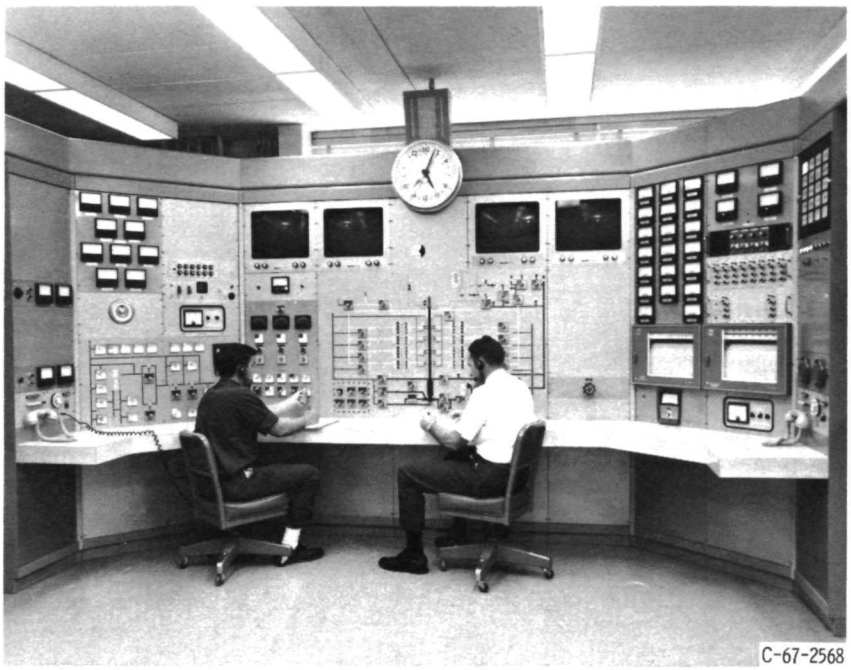
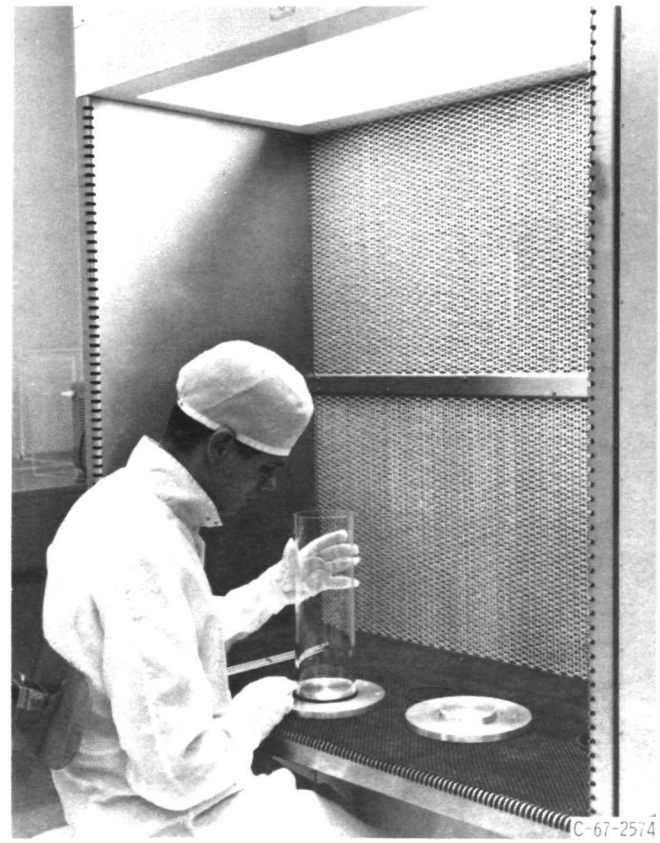


Figure 6. - Control room.



(a) Ultrasonic cleaning system.



(b) Laminar-flow work station.

Figure 7. - Clean room.



Figure 8. - Deceleration system.

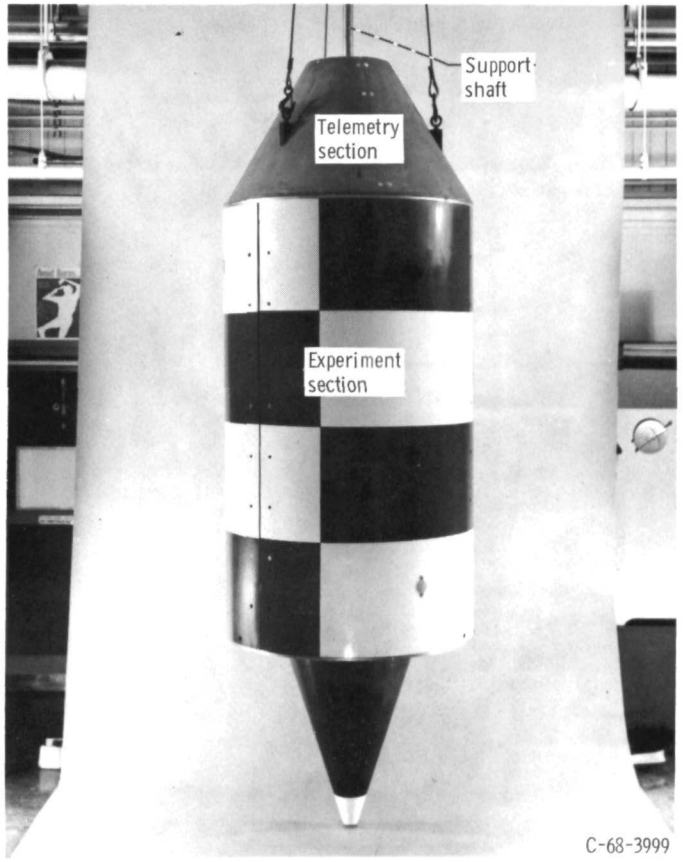


Figure 9. - Experiment vehicle.

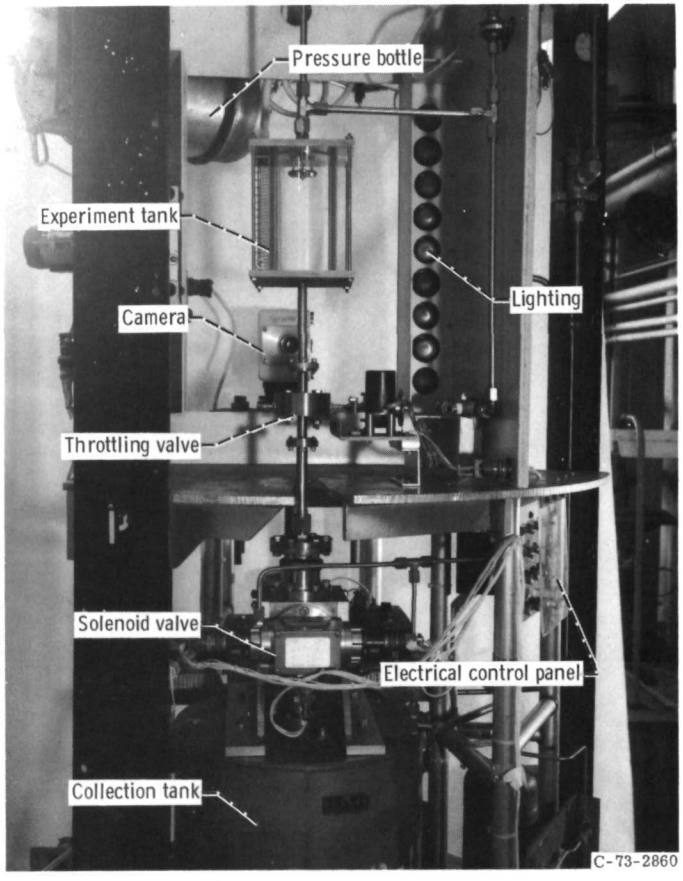


Figure 10. - Experiment package.

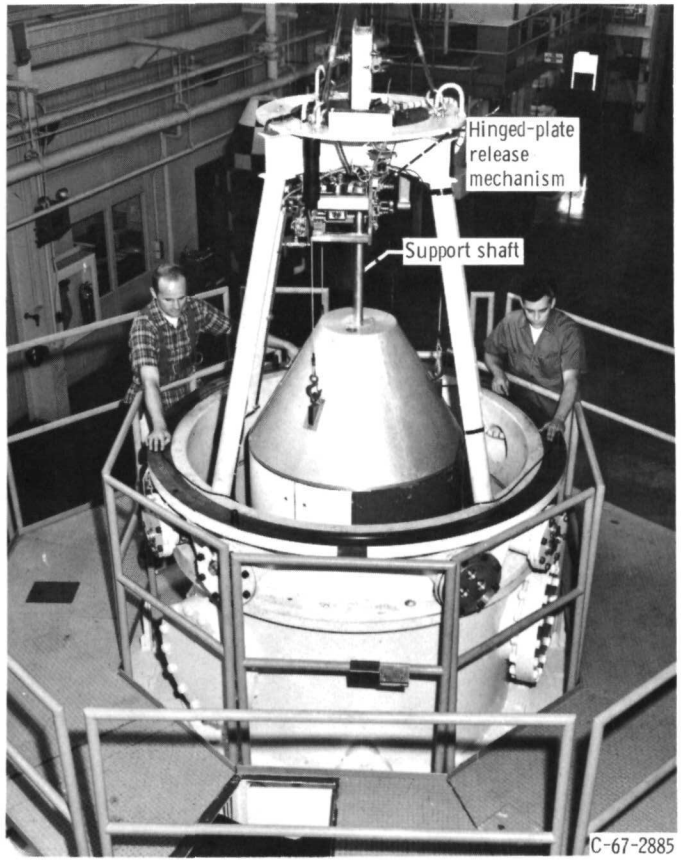


Figure 11. - Vehicle position prior to release.

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